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Morpho-physiological changes caused by soil compaction and irrigation on *Zea mays*

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Abstract

Physical properties of soil, such as compaction, have immense effects on the physico-morphological characters of plants, namely on the roots. For this reason per se, roots are immersed in a soil matrix with distinct conditions that may affect their anatomy, structure and function. Soil's physical characteristics, such as texture and compaction force, are some of the main factors affecting root growth and development. This study investigates how soil compaction, soil moisture and type of soil can modify the regular growth of *Zea mays* L., and thus reveal the changes influencing plant's physiology and growth. This experiment focuses on simulating two magnitudes of compaction (1.25 and 1.45 g cm^{-3}), two irrigation rates in two soil types, and assessing their effects on *Z. mays*. Despite intrinsic differences in the physico-chemical properties of the two soils, soil compaction had the highest influence on the decrease of leaf area, relative growth rate, total length of roots and shoot and dry mass of stem and roots, while it showed an increase in nitrate reductase activity and total chlorophyll content of the leaves and a limited bacterial growth. Soil moisture interactively aggravated the negative effects of soil compaction. In conclusion, soil compaction shows momentous effects on root anatomy and morphology during the seedling stage, with consequences on plant physiology and growth.

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Introduction

Concerns about soil compaction have increased due to the use of heavy machineries which reduce the potential for plant growth (Abu-Hamdeh, 2003), and thus limit root penetration and diminish water, air and nutrient availability (Kim et al. 2010; Tarawally et al. 2004; Whalley et al. 2008). However, compaction also features a declined length in primary and lateral roots, leaf area, absorption of nutrients and grain crop yield (Zhao et al. 2007), while it shows an increase in the shoot-to-root dry mass (Grzesiak, 2009). In general, high soil compaction has adverse effects on the growth and performance of plants (Alameda and Villar, 2012b), nevertheless, it is able to enhance growth of the shoot if the root-soil contact ameliorates and the nutrient movement in the soil increases (Tan and Chang, 2007), and thus a higher mineral nutrition (Arvidsson, 1999) and water absorption dominate (Kooistra et al. 1992). At the scale of the rhizosphere, compaction diminishes and limits optimal rhizosphere condition and microbial activity (Canbolat et al. 2006). In addition, many works have reported a strong negative correlation of microbial biomass carbon and nitrogen (Beare et al. 2006) and total nitrogen in compacted soils (Pengthamkeerati et al. 2011).

In this study, we tested the response of *Z. mays* to soil compaction and two irrigation rates under controlled conditions. The objectives of this study were first to evaluate what the plant's response is upon different

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treatments, and secondly to recognize if the model is able to represent how soil compaction affects root traits, and simultaneously show these changes on the level of the plant's functioning as a whole.

Material and Methods

Soil preparation

The two soils, S_1 and S_2, used in this study were collected from Al-Chahabieh (lat. 33°14'20.35"N, long. 35°22'25.18"E) and Tibnen (lat. 33°11'34.59"N, long. 35°24'34.92"E) from south Lebanon, respectively, representing soils of different natures; allowing the obtainment of a comparative study. Both studied soils were clay in nature, yet several physico-chemical characteristics were majorly different (Table 1).

Table 1. Al-Chahabieh (S1) and Tibnen (S2) soils characteristics.

Textural class		Soil type		NORME
		S_1 Clay	S_2 Clay	
Sand (%)		28.125	28.125	
Silt (%)		23.125	28.125	SOP METH004.00
Clay (%)		48.75	43.75	
Porosity (%)		46.17	46.87	Thien and Graveel 2003
Calcareous (%)	Total	71.6	7.3	NF ISO 10693
	Active	3.63	0.88	NF X-31-106
Conductivity (mS cm^{-1})		3.9	0.4	AFNOR X 31-113
pH		8.5	8	NF ISO 10390
Organic matter (%)		16.53	9.998	ASTM D 2974
Water holding capacity (mL L^{-1})		570	640	Thien and Graveel 2003

Soils were air-dried at ambient room temperature and sieved by a 7 mm mesh to remove coarse fragments. Consequently, they were compacted, according to Jusoff (1991), into cylindrical PVC tubes of 6 inch diameter and 50 cm height. For each soil, a bulk density of 1.25 and 1.45 g cm^{-3} was prepared for non-compacted (NC) and compacted (C) treatments respectively.

The studied system was composed of eight treatments, each consisting of a triplicate. The randomly arranged 24 pots underwent two irrigation rates of 240 and 350 mL per week (IR_1 and IR_2 respectively), contained two soil types (S_1 and S_2) and two bulk densities of 1.25 and 1.45 g cm^{-3}.

Growth conditions

This experiment was done in the laboratory of Plant Biology and Environment at the Lebanese University (Hadath). *Z. mays* was sown during the 100 day long experiment under controlled conditions of 12/12 h day/night period, 22/16 °C day/night temperatures, and 60-70% air moisture. Pre-germinated seeds were sown in the soil at a depth of circa 2 cm. All pots were manual weeded throughout the experiment. At the end of the experiment, the soils' mass water content (MWC in $g_{water}\ g_{soil}^{-1}$) was measured in a soil sample for each pot. That was done by calculating the difference between the wet and dry soil mass over the dry soil mass.

Plant measurements

After 100 days of growth, the number of leaves was counted and the height of each plant was measured (from soil level to the top leaf). Dry mass of root (DM_R) and shoot (DM_S) (dried at 80°C in an oven for two days) were determined, and the length of the roots was measured. The leaf area was measured by image analysis software (Image-Pro Plus v4.5; Media Cybernetic, Bethesda, MD, USA). Relative growth rate biomass (RGR_b in mg g^{-1} day^{-1}), specific leaf area (SLA in cm^2 g^{-1}), leaf mass ratio (LMR), stem mass ratio (SMR), root mass ratio (RMR), root length ratio (RLR in cm g^{-1}) and leaf area ratio (LAR in cm g^{-1}) were calculated according to Hunt (1990).

Leaf composition

At the end of the experiment, fully expanded and exposed leaves were randomly selected from each replicate of each treatment to measure the nitrate reductase activity (NRA) and total chlorophyll content ($Chl_{(a+b)}$). Total chlorophyll concentrations of those leaves were determined via a spectrophotometer (thermo spectronic) at 645 and 663 nm, and the calculations were effectuated according to Arnon (1949), whilst nitrate reductase activity was estimated in fresh leaves of the plants according to Jaworski (1971).

Bacterial counts

At harvesting time, after the columns were incised, the roots were separated from the bulk soil by gentle shaking (Fox and Comerford, 1992); soil still adhering to the roots (defined as rhizosphere soil) was collected by a dissecting probe (Benitez, 2000). Ten grams of soil from each sample was aseptically weighed, transferred to an Erlenmeyer flask with 100 mL sterile water and shaken for 30 min at 150 rpm. A series of 10-fold dilutions of the suspension was made for each sample till 10^8-fold dilution was reached; 0.1 mL of each dilution of the series was placed onto a Petri dish with nutrient agar (Difco). Three replicates were made for each dilution. Finally, incubation and calculation of average CFU (Colony forming unit) per gram of oven-dried soil was calculated according to Pepper and Gerba (2004).

Statistical analysis

Statistical analyses were performed using SPSS statistics 17.0. Data were subjected to analysis of variance (ANOVA) at $P<0.05$ and $P<0.01$ to assess statistical significance of compaction, irrigation, soil type and their interactive effects. Duncan's multiple range test (α=5%) was performed to analyze statistical differences between different treatments for each parameter.

Results

Soil moisture

The moisture content of a soil is of great importance, since it is a vital aspect for soil microbiota. Furthermore, aerobic or anaerobic condition of the soil is affected by the moisture content; for water in the soil compartment is able to modify the porosity. Figure 1 shows the influence of each treatment on MWC, where it varied significantly with irrigation rate and soil type, this implies that MWC changes with irrigation coupled with soil type.

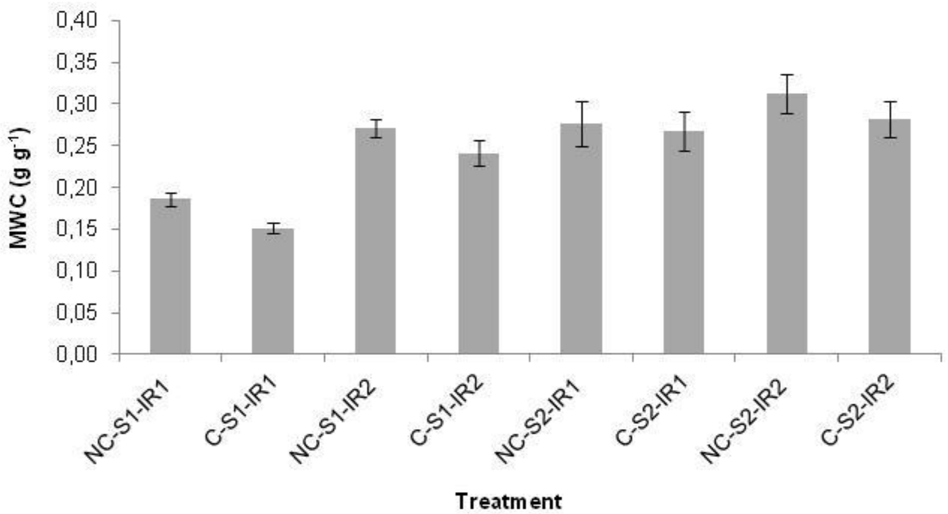

Figure 1. Fluctuation of MWC for different treatments

Consequences on growth traits

Leaf number was not affected in all the treatments, whereas a significant decrease was observed in leaf area *vis-a-vis* soil type, irrigation rate, and compaction (Table 2). The interactive effect of compaction and irrigation rate exhibits a significant difference in leaf area and stem and root length (Table 7), which means that latter is dependent on the former. In all treatments, soil compaction lead to a significant decrease in root length, the latter is greatly and significantly affected by soil type and S*C. In the same way, the length of the stem was negatively affected by soil compaction with significant difference in IR_2 treatments.

DM_S showed a significant interaction between C*IR and S*C*IR (Table 7). Most treatments showed a decrease in DM_S with increasing compaction, all except S_1-IR_1 are significant (Table 3). Soil type, compaction and irrigation, separately, and C*IR had a decreasing influence on DM_R. When comparing all treatments, DM_R is significantly different in IR_2 treatments for C and NC soils. Compaction, soil type and C*IR have a significant effect on DM_S, DM_R and DM_{S+R}, the latter shows a significant interaction with S*C*IR, where a reduction in the dry matter is observed in all treatments except for S_2-IR_1 ones, where the DM_{S+R} is increased by 21.43%. DM_S/DM_R varies significantly only with irrigation; it also witnessed an increase for C treatments over NC ones in IR_1, while the opposite is true for IR_2.

Table 2. Fate of leaf features of maize seedlings attributable to different treatments.

Treatment	Leaf number		Leaf Area (cm²)		Length (cm)			
					Stem		Root	
NC-S_1-IR_1	14 ±1.4	a	800 ±56.6	a	87.8 ±7.92	ab	29 ±1.41	a
C-S_1-IR_1	14 ±1.4	a	654 ±76.36	bc	73.05 ±6.01	bc	20 ±2.82	de
NC-S_1-IR_2	14.7 ±1.5	a	913 ±60.8	a	90.2 ±1.8	a	38.3 ±4.9	b
C-S_1-IR_2	14 ±1.4	a	445.5 ±54.45	d	60.45 ±10.96	c	17 ±1.41	e
NC-S_2-IR_1	13.5 ±2.1	a	536 ±48.08	cd	78.7 ±12.02	ab	50.8 ±0.35	c
C-S_2-IR_1	14 ±1.4	a	572.5 ±31.8	bc	81.5 ±7.78	ab	29.5 ±0.71	a
NC-S_2-IR_2	14.5 ±0.7	a	665.8 ±18.7	b	89.1 ±2.7	ab	52 ±2.8	c
C-S_2-IR_2	12 ±1.4	a	179.5 ±43.1	e	59.3 ±1.8	c	25 ±2.8	ad

Note: Means within columns followed by the same letter do not differ significantly according to Duncan's multiple range test (α=0.05).

Table 3. Dry mass of maize seedlings attributable to different treatments.

Treatment	DM_S (g)		DM_R (g)		DM_{S+R} (g)		DM_S/ DM_R	
NC-S_1-IR_1	2.714 ± 0.22	a	0.43 ±0.099	abc	3.144 ±0.32	a	6.419 ±0.95	ab
C-S_1-IR_1	2.395 ±0.02	ac	0.275 ±0.035	cd	2.67 ±0.014	acd	8.78 ±1.2	ab
NC-S_1-IR_2	3.772 ±0.3	b	0.626 ±0.1	a	4.39 ±0.3	b	6.04 ±0.4	ab
C-S_1-IR_2	1.8 ±0.14	d	0.387 ±0.089	bc	2.167 ±0.22	d	4.738 ±0.72	a
NC-S_2-IR_1	2.05 ±0.27	cd	0.265 ±0.049	cd	2.31 ±0.32	cd	7.75 ±0.4	ab
C-S_2-IR_1	2.65 ±0.02	a	0.3 ±0.13	cd	2.94 ±0.16	ac	9.98 ±3.1	b
NC-S_2-IR_2	3.6 ±0.5	b	0.5 ±0.1	ab	4.1 ±0.7	b	7.1 ±1.1	ab
C-S_2-IR_2	0.98 ±0.01	e	0.145 ±0.04	d	1.098 ±0.05	e	6.98 ±1.78	ab

Notes: Means within columns followed by the same letter do not differ significantly according to Duncan's multiple range test (α=0.05).

RGR_b is higher in plants embedded in NC soils, except for S_2-IR_1 (Table 4). Both LMR and SMR are dependent on C*IR, S*C and S*C*IR (Table 7); however the first is also affected by irrigation. LMR increases and SMR decreases insignificantly with compaction in all treatments except S_2-IR_1. SLA is affected significantly by soil type and irrigation, though only S_2-IR_1 shows an increase at compaction levels. A negative yet insignificant relation lies between LAR and soil compaction in all treatments, nonetheless, it is significantly affected with soil type and irrigation rate.

Table 4. Response of plant's growth to different treatments.

Treatments	RGR_b (mg g^{-1} day^{-1})		LMR		SMR		SLA (cm^2 g^{-1})		LAR (cm^2 g^{-1})	
NC-S_1-IR_1	29.14 ±0.002	a	0.452 ±0.022	ab	0.411 ±0.005	ac	563.7 ±8.68	a	254.9 ±8.44	a
C-S_1-IR_1	26.59 ±0.0001	ac	0.495 ±0.05	b	0.403 ±0.04	a	500.57 ±76	abc	244.87 ±27.3	ab
NC-S_1-IR_2	33.7 ±0.001	b	0.4 ±0.04	ab	0.455 ±0.03	acd	521.4 ±64.7	ab	208.43 ±23.5	abc
C-S_1-IR_2	23.387 ±0.002	c	0.447 ±0.03	ab	0.377 ±0.008	a	456.2 ±39.3	abc	203.42 ± 0.58	bc
NC-S_2-IR_1	24.3 ±0.002	c	0.59 ±0.06	c	0.29 ±0.05	b	393.7 ±19	cd	232.87 ±12	ab
C-S_2-IR_1	28.1 ±0.001	a	0.39 ±0.05	a	0.506 ±0.01	d	495.8 ±5.84	abc	195.29 ±21.2	bc
NC-S_2-IR_2	33.3 ±0.003	b	0.4 ±0.04	a	0.48 ±0.03	cd	420.26 ±8.8	bcd	164.09 ±21.5	c
C-S_2-IR_2	12.5 ±0.001	d	0.49 ±0.03	ab	0.38 ±0.06	a	324 ±45.1	d	159 ±31.7	c

Notes: Means within columns followed by the same letter do not differ significantly according to Duncan's multiple range test (α=0.05).

As for RMR, it was significantly and solely affected by irrigation (Table 7), with a higher RMR for IR_2 treatments over IR_1 ones. RLR, on the other hand was significantly influenced by compaction, soil type, their interaction and C*IR, with a superior value for NC and S_2 over C and S_1 respectively (Table 5).

Table 5. Root performance in different treatments.

Treatments	RMR		RLR	
NC-S_1-IR_1	0.136 ±0.01	ab	1.075 ±0.052	a
C-S_1-IR_1	0.100 ±0.01	b	0.740 ±0.100	ed
NC-S_1-IR_2	0.142 ±0.01	ab	1.420 ±0.200	b
C-S_1-IR_2	0.174 ±0.02	a	0.63 ±0.050	e
NC-S_2-IR_1	0.114 ±0.01	b	1.88 ±0.010	c
C-S_2-IR_1	0.099 ±0.04	b	1.09 ±0.030	a
NC-S_2-IR_2	0.124 ±0.02	b	1.925 ±0.100	c
C-S_2-IR_2	0.128 ±0.03	ab	0.925 ±0.100	ad

Notes: Means within columns followed by the same letter do not differ significantly according to Duncan's multiple range test (α = 0.05).

Physiological outcomes

The total chlorophyll content (Chl $_{(a+b)}$) of the plants was found to be lower in NC soils for all treatments. Moreover, it had a positive relationship with increasing irrigation rate for S_1, while the opposite is true for S_2. The last statement is also true for NRA. Plus, NRA generally increased in compacted soil, with the highest of a 42.56% increase from non-compacted to compacted S_1-IR_2 (Table 6).

Table 6. Plant's physiology variation.

Treatments	NC-S_1-IR_1	C-S_1-IR_1	NC-S_1-IR_2	C-S_1-IR_2	NC-S_2-IR_1	C-S_2-IR_1	NC-S_2-IR_2	C-S_2-IR_2
NRA (ηmol $NO_2^- g^{-1} h^{-1}$)	58.4	48.3	69.3	98.8	47.1	48	42.7	44.4
Chlorophyll$_{(a+b)}$ (μg mL^{-1})	20.45	24.43	23.46	25.48	23.99	25.81	12.26	14.43

Table 7. Percentage of influence of each variable on the proposed parameters using eta square (SPSS 17.0).

Variables	Soil		C		IR		S*C		S * IR		C*IR		S*IR*C		Error
Stem length (cm)	0.08	ns	50.22	**	4.79	ns	2.98	ns	0.03	ns	22.26	**	3.07	ns	16.58
Root length (cm)	27.82	**	61.36	**	0.09	ns	3.19	*	0.91	ns	3.25	*	0.43	ns	2.94
Leaf Area (cm^2)	25.42	**	38.98	**	4.44	**	0.92	ns	0.97	ns	24.58	**	1.40	ns	3.29
Leaf number	6.28	ns	6.28	ns	0.10	ns	1.57	ns	2.45	ns	11.88	ns	4.81	ns	66.62
DM_R (g)	15.45	*	33.54	**	10.38	*	0.19	ns	2.71	ns	14.60	*	6.18	ns	16.97
DM_S (g)	4.14	*	37.81	**	0.23	ns	0.16	ns	0.73	ns	48.16	**	4.90	**	3.88
DM_{S+R} (g)	5.62	*	38.47	**	0.84	ns	0.18	ns	0.96	ns	43.40	**	5.29	*	5.24
DM_S/ DM_R ratio	13.44	ns	3.90	ns	25.49	*	0.42	ns	0.24	ns	14.23	ns	0.67	ns	41.60
LMR	1.55	ns	0.04	ns	13.31	*	11.10	*	0.03	ns	28.56	**	27.12	**	18.30
SMR	0.15	ns	0.18	ns	2.48	ns	13.15	*	0.87	ns	49.55	**	20.31	**	13.32
RMR	16.86	ns	0.28	ns	29.12	*	0.22	ns	3.07	ns	14.84	ns	4.37	ns	31.24
SLA ($cm^2 g^{-1}$)	39.04	**	3.52	ns	12.61	*	4.23	ns	0.81	ns	9.42	ns	9.03	ns	21.35
LAR ($cm^2 g^{-1}$)	30.31	**	3.92	ns	43.91	**	0.89	ns	0.34	ns	1.67	ns	0.90	ns	18.06
RGR_b (mg g^{-1} day^{-1})	8.01	**	34.21	**	1.09	ns	0.61	ns	2.42	*	40.14	**	10.66	**	2.85
RLR	27.68	**	61.54	**	0.10	ns	3.20	*	0.91	ns	3.20	*	0.43	ns	2.93
MWC	48.11	**	6.23	*	29.34	**	0.38	ns	9.06	**	0.17	ns	0.40	ns	6.30
Bacteria	1.76	ns	34.40	**	45.53	**	0.06	ns	13.24	**	0.003	ns	0.23	ns	4.78

Note: **: significance at *P<0.01*; *: significance at *P<0.05*; ns: not significant.

Microbial Populations

The number of bacteria was significantly affected by soil compaction in all treatments, soil type in IR_1 treatments, irrigation for S_2 soils and soil-irrigation interaction for all, indicating that the effect of soil type on bacterial growth is irrigation-dependent. As a result of compaction, bacterial growth decreased, especially in IR_2 treatments, with a 16.72% decrease between NC-S_2-IR_2 and C-S_2-IR_2 (Figure 2).

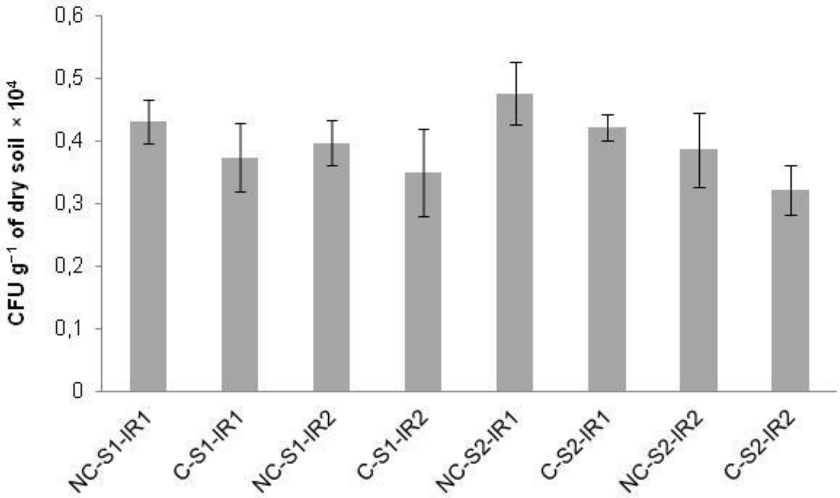

Figure 2. Dynamics of bacteria in the rhizosphere

Percentage of variation on the parameters

According to Table 7, compaction has the highest share of influence on length of stem and root, leaf area, DM_R, RLR and MWC, while C*IR explains most of the variation of DM_{S+R}, DM_S, LMR, SMR and RGR_b. However, some variable were independent of treatment, and as much as 66.61% counted as error for leaf number.

Discussion

Consequences of studied parameters on the fate of Zea mays L.

Our Chief objective was to figure out the plant's morphological and physiological responses caused by different treatments. Interestingly, most variables in this study were mainly influenced by compaction, which is dependent on irrigation (i.e. C*IR), and sparsely on soil type (Table 7). In this sense, the results obtained in this study indicate that the DM_R accumulation of *Z. mays* was significantly limited by soil compaction. As for DM_S, it was reduced due to the decline in leaf area and potential diminution of plant growth (Grzesiak, 2009; Grzesiak et al. 2012; Lipiec et al. 1996; Tippkotter, 1983). Furthermore, compaction or water saturation are able to reduce the shoot and root growth, number of leaves, leaf area, biomass and relative growth rate (Table 2, 3 and 4) (Alameda et al. 2012a; Hoffmann and Jungk, 1995; Konôpka et al. 2008; Montagu et al. 2001; Tardieu, 1991). Ultimately, the following sequence following compaction is: root distortion, shoot impairment, architecture changes and root anatomic acclimatization (Alameda and Villar, 2012b).

Moreover, DM_S/DM_R tended to increase with IR_1, which his triggered by the reduction in DM_R in compacted treatments. Whilst in IR_2 treatments, the reduction in DM_S/DM_R is due to the important reduction in DM_S of the compacted treatments (Grzesiak, 2009; Konôpka et al. 2008). In addition, this study reveals a contradiction in few studies regarding the decrease in the total chlorophyll content of plants sowed in compacted soils. Nonetheless, Campostrini et al. (2002) undertook an experiment where one out of four *Carica papaya* L. genotypes showed an increase in $Chl_{(a+b)}$, which is the case of all treatments in this study. On a separate note, the NRA was mainly dependent on moisture and soil type, while there was no obvious relation according to compaction level. However, Engelaar et al. (1995) found that NRA is rather dependent on plant species.

The constructive effects of soil compaction

SLA, SMR and LAR showed a decrease in response to soil compaction generally in all treatments, excluding S_2-IR_1, which could be due to compaction, which in turn is related in increasing nutrient per volume unit (Arvidsson, 1999) and water absorption (Kooistra et al. 1992). This notion is contrary to the general one that soil compaction negatively affects plants' performance (Grzesiak et al. 2012). RMR was higher for IR_2, thus a larger root system was able to develop (Table 5); this goes back to the reason that penetration resistance is inversely proportional to moisture content (Konôpka et al. 2008). Similarly, some literatures have found a positive effect of soil compaction, such as biomass, dry matter and height of plant (Alameda et al. 2012b), this accords with the results of S_2-IR_1. Moreover, in spite of the positive effect of a compacted soil on the total biomass for some species, the architecture of the plants is shown to be negatively affected, notably the root mass ratio and root length ratio.

High moisture coupled with compaction aggravates the unconstructive effects of soil compaction

As expected and stated by Soane and Van Ouwerkerk (1994), compaction and high water availability negatively modifies growth by decreasing the penetration resistance of the roots (Konôpka et al. 2008). The growth of roots requires pores ranging from 100 to 200 mm in diameter, so the reduction of large pores in compacted soils would therefore limit air exchange and root development (Thien et al. 2003). From an agronomic point of view, this means that the adverse effect of clods can be alleviated, and thereby, crop production would be increased via a proper irrigation system. Remarkably, in our study, higher irrigation rates did aggravate the negative effects of soil compaction, which is probably related to reduction in gas diffusion rate and O_2 availability that induce the shift from nitrification to denitrification (Pupin et al. 2009).

Microbial Populations

Soil compaction is able to alter the enzymatic activity and reduce the biomass of the soil's microbiota, and consequently modifying plant-available nutrients, thus influencing the plant's growth (Canbolat et al. 2006; Li et al. 2002). Results of this study showed a decrease in the total number of the bacterial community in the compacted soil, just as reported by Smeltzer et al. (1986). The results of Pupin et al. (2009) showed that the total number of bacteria decreased progressively and significantly at different depths of compacted soil.

Conclusion

In this work, a great variability of responses to solely soil compaction has been found. The effects of a compacted soil generally showed inferior characteristics, such as leaf area, RGR_b, RLR, root and shoot length (due to mechanical stress), DMs , DM_R and DM_{S+R}, while the effect of irrigation was significantly regressing leaf area, DM_R, DM_S/DM_R, LMR, LAR and RMR. It is worth mentioning that S_2-IR_1 treatments matchlessly showed an increase in some parameters for higher compaction (leaf area, stem length, RGRb, SMR, SLA, DMs, DM_R, and DM_{S+R}). Those modifications are translated into changes in physiology and architecture of *Z. mays*. It seems that changes in the plant physiology may be linked by the root's exploring capacity (nutrient and water uptake) being limited by soil compaction. The interaction between water content and compaction levels was clearly shown in the growth of *Zea mays* seedlings. Soils irrigated with 350 mL per week worsened the effects of soil compaction. Those modifications are translated into changes in architecture at the whole-plant level. Moreover, values of NRA and $Chl_{(a+b)}$ were higher in compacted soils, while the bacterial count was reduced by 11-13% in the compacted soils when compared to the control.

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